RESTRICTED CIRCULATION

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Estimating the frequency of offensive odours in the vicinity of livestock enterprises: a case-study for Norfolk

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1. Introduction

A large turkey unit in Norfolk is sited close to a small village to which it presents a substantial odour nuisance from time to time. It seems unlikely at present that any very effective and economical measures for control of odours released from the unit's buildings can be introduced. However, the odour problem occurs in the village for a restricted wind sector only, and will be less serious under conditions when rapid atmospheric dispersion takes place. An objective assessment of the likely frequency and magnitude of the odour in the village is useful in these circumstances. First it can be used to refute any subjective, exaggerated claims which might be made by residents that the odours arrive frequently and in high concentrations. Second it may be employed to define the periods in which an odour-abatement technique, such as masking, which could be applied intermittently to reduce cost, would be needed. A method will now be described for estimating the frequency and relative magnitude of odours experienced at a point fixed in relation to a nearby odour source. The results obtained when the method is applied to the Norfolk turkey unit are also discussed.

2. Framework of analysis

The odour source (Figure 1) is assumed to be distributed among a number of buildings on a site of width Y, which is at an average distance X from a point (A) where the odour is to be evaluated. The bearing of the site's centre (B) from A is θ degrees from North. Rapid lateral mixing in the vicinity of the buildings allows the source to be treated as if approximately uniform across the site in those cases where X is several times larger than Y. The odour emission rate is postulated to be constant throughout the year: this is not a restrictive assumption because the analysis to be described is performed on a monthly basis, and the results may be readily corrected for any seasonal variation in odour emission.

As the distance downwind from the odour site increases, the lateral dispersion (and consequent odour dilution) due to atmospheric turbulence becomes increasingly important. The consequences of lateral dispersion are described most conveniently by first considering an odour emission from a continuous point source (Figures 2 and 3). At any instant the odour spreads downwind as a relatively narrow plume (the "instantaneous" plume). However, larger-scale turbulent eddies cause the plume to meander, so that the plume sampled over a period of 10 minutes or so (the "time-mean" plume) is several times wider than the instantaneous plume. Figure 4 shows these ideas applied to the case where the source is uniformly distributed over a finite area: at this stage the effects of vertical diffusion on odour concentration have been ignored. Close to the source (a) concentrations on the

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average centreline of the plumes' position will be the same for both instantaneous and time-mean plumes. Some way further downwind (b) concentrations at the centreline of the instantaneous plume will be unchanged, but plume meandering will decrease the time-mean concentration. Finally, at greater distances (c) lateral diffusion will have completely eroded the plateau in concentration of even the instantaneous plume, so that the highest concentrations in both plumes are then decreasing with increasing distance.

Dilution of the odour plume is also caused by vertical turbulent mixing. Eddies produced by the buildings on their downwind side mix odours up to about twice the building height, within a few building heights downwind (eg. Cloyne 1954). Away from the immediate influence of the buildings, atmospheric turbulence will steadily deepen and hence dilute the odour plume as distance downwind increases. Vertical diffusion is most rapid in unstable, and least in stable conditions.

In a case where the source is at ground level the distribution of concentration with height at a point downwind is approximately gaussion, with the maximum at ground level. Pasquill (1961) showed that the standard deviation of this distribution (about an axis at ground level) could be expressed in terms of distance downwind from the source and a simple stability parameter. This parameter is readily estimated from wind speed, time of year and cloud cover (Table 1). The rate of vertical diffusiion varies slightly with surface roughness.

TABLE 1

Pasquill's stability categories

10 m wind (ms^{-1})	Insolation			Night	
	Strong	Moderate	Slight	$\geq$4/8 low cloud	<4/8 cloud
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Strong insolation ≡ sunny midday in summer
Slight insolation ≡ sunny midday in winter
Night ≡ 1 hr before sunset to 1 hr after dawn
Category D is used in overcast conditions and for the hour preceding or following night as defined above

Smith (1973) suggested a typical roughness length for diffusion over rural land with small villages is about 0.3m, but a rather smaller value (around 0.1m) is probably appropriate in the present case where the interest is chiefly in following odours from isolated farms to the nearest non-farming habitations. Pasquill's original estimates for the variations of σ_z with distance have been refined by Smith (1973), and Hosker (1974); a simple analytical representation of Hosker's values of σ_z in terms of X for different stabilities is given in Table 2.

Table 2. Estimates for σ_z for a roughness length of 0.1m

$$\left(\sigma_z = \frac{a X^b}{1 + cX} \right)$$

Stability Category	a	b	c
A	0.105	1.07	1.11×10^{-4}
B	0.125	0.96	$.73 \times 10^{-4}$
C	0.11	0.92	$.64 \times 10^{-4}$
D	0.095	0.89	$.80 \times 10^{-4}$
E	0.066	0.87	$.76 \times 10^{-4}$
F	0.062	0.78	$.60 \times 10^{-4}$

In the obstructed flow of the present case the effective initial source is not at ground level but is distributed, as explained earlier, more or less uniformly with height up to about twice the building height. Consequently, the decline in near-surface odour concentration with distance, caused by vertical diffusion alone, is less rapid than for a source at ground level. A simple method of allowing for the effects of vertical atmospheric diffusion on odour dilution, which also provides a rough correction for the consequences of mixing in the building wakes, involves the introduction of an upwind virtual source at ground level which replaces the actual odour source (Figure 5). The two source strengths are assumed to be equal. The distance (X') of the virtual source upwind from the real source is clearly a function of atmospheric stability, being least in unstable conditions. However, the vertical distribution of concentration in the plume from the virtual source will be Gaussian, and the question then arises of the best method of matching this distribution to that just downwind from the odour site, assumed to be constant up to twice the building height. The approach which will be adopted here is to site the virtual source at such a distance that the virtual and actual surface concentrations are the same at the odour site, and the standard deviation of the vertical distribution of concentration in the virtual plume at this distance is approximately $1.6h$ where h is the building height: the concentrations integrated over the height of the actual and virtual plumes just downwind from the site's centre will then be equal (Pasquill 1961). Corresponding values of X' for different stabilities and various building heights are given in Table 3.

Table 3. Upwind distance (X') of virtual source for different atmospheric stabilities and building heights

Stability Category	X' (m)						
	h =2	3	4	5	6	8	10
A	25	35	45	55	70	85	110
B	30	45	60	75	90	125	160
C	40	60	85	105	130	180	220
D	55	80	115	140	175	250	330
E	90	140	200	265	330	450	590
F	160	265	400	540	700	1050	1450

The Norfolk turkey unit lies about 300m from the closest part of the nearby village. Ignoring the consequences of lateral diffusion for the moment, the effects of vertical diffusion will be to reduce the odour (C_v) at the village to a value given by

$$C_v = C_u \frac{\sigma_z(X')}{\sigma_z(X+X')} \qquad (1)$$

where

C_u = odour concentration immediately downwind from unit
$\sigma_z(X')$ = standard deviation of vertical distribution of odour produced at the unit by the virtual source
$\sigma_z(X+X')$ = standard deviation of odour distribution at village ($X = 300m$)

The values in Table 3, and Hosker's data may then be used to calculate C_v/C_u for the various stability categories (Table 4): a building height of 4m has been used.

Table 4. Odour dilution factor (C_v/C_u) due to vertical diffusion

	Stability category					
	A	B	C	D	E	F
C_v/C_u	0.12	0.18	0.25	0.34	0.47	0.67

It is important to note that these calculated dilutions are for a non-buoyant release of odour. In practice, and particularly at night in winter, the odiferous air passing out from the buildings will be warmer than the ambient air. The elevation in temperature might be as high as 10 deg C, and if this air is expelled in near-calm, inversion conditions much of the odour might move away from the site as an elevated plume which could pass above the receptor. However, the assumption will still be made here that significant mixing will occur in the vicinity of the unit's buildings, up to twice building height, in order to maintain the simplicity of the method of analysis.

The treatment of the effects of lateral dispersion on odour strength at the receptor is simplified by considering first the source as a point producing, for a particular wind direction, a plume of material which fluctuates laterally; the source is then integrated over the whole emission area, and the wind direction over a sector wide enough for all significant contributions to odour frequency at

the receptor to be included. The instantaneous plume is assumed to contain material which is distributed acrosswind gaussianly, with a standard deviation $\sigma_{yI}(x)$ at the distance of the receptor. The time-mean plume is also gaussian with standard deviation $\sigma_{yM}(x)$. The acrosswind distribution of the centreline of the instantaneous plume over the sampling period is then approximately

$$\sigma_{yc}(x) = \left(\sigma_{yM}(x)^2 - \sigma_{yI}(x)^2\right)^{1/2} \qquad (2)$$

For convenience, the sampling time for the time-mean plume is taken to be 1 hour, to be consistent with synoptic data archives. Referring to Figure 6, the probability $P_{I,y}$ of the axis of the instantaneous plume being within a range of crosswind distances y to $y+dy$ from the receptor, for a mean wind direction which lies at an angle ϕ off the direct line from source to receptor is

$$P_{I,y} = \frac{1}{2\sqrt{2\pi}\,\sigma_{yc}^2}\left(\exp\left(-\frac{(y-x\phi)^2}{2\sigma_{yc}^2}\right) + \exp\left(-\frac{(y+x\phi)^2}{2\sigma_{yc}^2}\right)\right)dy \qquad (3)$$

: note that the instantaneous plume may pass either side of the receptor, leading to the two terms on the right hand of the equation. At the crosswind distance y, the concentration in the instantaneous plume is

$$\chi_y = A\exp\left(-\frac{y^2}{2\sigma_{yI}^2}\right) \qquad (4)$$

where A is the concentration on the centreline of this plume.

Consider now the case where source is not a point, but is a line of length L, assumed for convenience to be perpendicular to the instantaneous flow (Figure 7): the concentration at R, distance y acrosswind from the alongwind line through the source centre, and X downwind from the line, due to an element of length ds, distance s from the centre of the source line is

$$C(X,y) = \frac{QF\,ds}{LU\sigma_{yI}\sqrt{2\pi}}\exp\left(\frac{(y-s)^2}{2\sigma_{yI}^2}\right) \qquad (5)$$

where

F = factor to allow for dilution of concentration by vertical diffusion (= constant $\times C_v/C_u$)
Q = total source strength
U = wind speed

Integrating over the length of the source line, which is assumed to emit uniformly along its length

$$\Sigma C(X,y) = \frac{QF}{2LU}\left(\mathrm{erf}\left(\frac{y+L/2}{\sigma_{yI}\sqrt{2}}\right) - \mathrm{erf}\left(\frac{y-L/2}{\sigma_{yI}\sqrt{2}}\right)\right) \qquad (6)$$

where

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

Eq (3) and (6) are then used in a computer program to provide the required odour frequency data, along the following lines.

(i) The direction from receptor to centre of the source area is determined.

(ii) A data-sorting program is used in conjunction with hourly meteorological data from a meteorological station as close as possible to the site to provide the frequency of occurrence of wind direction in 10 degree bands up to 50 degrees on either side of the receptor-source line, month-by-month for a 10-year period.

(iii) These frequencies, for each 10 degree band, are sorted according to wind speed and cloud amount, and from these into wind speed/stability classes, separately for day and night, for each month.

(iv) Values of σ_{yM} (X =300m) and σ_{yI} (X =300m) are estimated (Clarke, 1979; Smith and Hay, 1961): values are given in Table 5.

Table 5. Horizontal standard deviations of odour concentration in instantaneous and time mean (1 hour sampling) odour plume 300m from point source of odour

	Standard deviations (m)					
	A	B	C	D	E	F
σ_{yI}	24	18	15	12	8	5
σ_{yM}	80	59	44	28	34	40

(v) For each wind speed range and stability category the odour concentration is estimated at the receptor, using eq (6), for angular deviations up to 50 degree from the instantaneous plume centre line, at 1 degree intervals.

(vi) The probability of the centre line of the instantaneous plume, for each 10-degree interval of wind direction, being within a certain angular distance of the receptor-source line is determined from eq (3) for each stability category.

(vii) Values from steps (iii), (v) and (vi) are then combined to yield finally the probability (expressed in hours per month for each month, separately for day and night) of certain odour concentrations being experienced at the receptor.

(viii) The results from step (vii) are inconveniently expressed, because the number of specific odour concentration values involved is of the order of 500: the probabilities are therefore combined to yield probabilities of odour concentrations in the ranges 0_{max} to $0_{max}/2$, $0_{max}/2$ to $0_{max}/4$, ..., $0_{max}/2^{i}$ to $0_{max}/2^{i+1}$,.. etc; here 0_{max} is the odour strength experienced when the odour plume blows directly from the source area to the receptor on occasions with class F stabilities and the lowest wind speed range.

3. Data

Hourly observations for the 10-year period 1972-1981 from Marham (about 45km NE of the turkey unit) were used in the analysis. The centre of the turkey unit bears around 100 degrees from the assumed receptor, with the whole unit

subtending an angle of approximately 20 degrees at the receptor. A frequency analysis was carried out on a monthly basis (all 10 years combined), separately for day and night, for 10-degrees wind sectors centred from 050 to 160 degrees. Three wind speed classes were used in the frequency sub-division: 1-4 kts, 5-9 kts, $\geq$ 10 kts, with assumed average value of 1.3, 3.6 and 7 m/s. Two cloud classes were also used; by day the frequency data were assigned according to cloud being $\leq$ 6/8 or $>$ 6/8 at the time of the wind observation, and at night the classes were 0-4/8 and $\geq$ 5/8. Each observation was then assigned to a stability category according to Table 1. The classification schemes used are shown in Table 6.

Table 6. Stability classification for wind frequency analysis

(a) Night-time (all months)

Speed range (Kts)	Pasquill stability categories	
	$<$ 5/8 cloud	$\geq$ 5/8 cloud
1-4	F	E
5-9	E	D
$\geq$10	D	D

(b) Daytime

Speed range (Kts)	Pasquill Stability Categories											
	Jan		Feb		Mar		Apr		May		June	
	(1)	(2)										
1-4	C	D	B	D	B	C	B	C	A	B	A	B
5-9	C	D	C	D	C	D	C	D	B	C	B	C
$\geq$10	D	D	D	D	D	D	D	D	C	D	C	D
	Jul		Aug		Sep		Oct		Nov		Dec	
1-4	A	B	A	B	B	C	B	C	B	D	C	D
5-9	B	C	B	C	C	D	C	D	C	D	C	D
$\geq$10	C	D	C	D	D	D	D	D	D	D	D	D

(1) $<$ 7/8 cloud
(2) $\geq$ 7/8 cloud

All months included some observations of "calms". These were analysed by dividing the reported frequencies equally between all wind directions (0-360 degrees) and then assigning them to the lowest wind speed range.

4. Results and discussion

The complete frequency analysis is presented in Table 7, separately for day and night: odour frequencies are given as the average number of hours per month, for each month of the year, over a range of concentrations from O_{max} down to $O_{max}/1024$; odours at lower concentrations are assumed to be inoffensive. The most offensive odours are seen to occur most frequently at night, reflecting the generally lower wind speeds and greater atmospheric stability then: seasonal peaks of odour strength appear in late winter/early spring and late summer/autumn when winds from the easterly quarter are most frequent. In the worst month (February) odours with strength greater than $O_{max}/8$ occur for about 1 hour per day on average, but the most offensive odours ($\geq O_{max}/2$) are found for an average of only 15 minutes per day, almost completely during night-time. These and the corresponding figures for other months provide some guidelines for assessing the cost of masking. More accurate costings can be made if the threshold of offensiveness (in terms of dilutions from O_{max}) can be established: the values to the left of this threshold in Table 7 can then be summed to give probable monthly (and hence daily) duration of odours above the threshold.

Any comments or suggestions on this paper should be referred to the authors.

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Table 7. Estimated odour frequencies at village edge

Month	Period	Frequency of odours (hours/month) within stated concentration range								
		a^*	$a/2$	$a/2^2$	$a/2^3$	$a/2^4$	$a/2^5$	$a/2^6$	$a/2^7$	$a/2^8$	$a/2^9$
Jan	D	7.3	9.4	24	34	11	5.8	9.3	8.1	4.1
	N	33	9.2	47	77	18	14	13	16	8.1
Feb	D	7.6	9.7	61	86	27	13	21	17	10
	N	62	29	109	104	29	23	25	23	15
Mar	D	0	14	61	80	23	13	19	14	10
	N	45	24	65	64	20	15	17	14	11
Apr	D	0	13	29	31	11	7.2	10	6.9	5.0
	N	25	14	34	29	8.4	7.5	7.6	6.9	4.8
May	D	0	5.8	36	184	77	33	38	32	17
	N	33	27	55	61	17	12	15	10	11
Jun	D	0	5.9	35	63	26	14	20	11	11
	N	29	14	29	17	6.7	7.5	7.8	5.5	5.3
Jul	D	0	8.3	37	77	36	19	23	16	10
	N	38	18	31	20	6.9	8.2	7.5	6.7	4.9
Aug	D	0	10	57	134	59	30	41	24	20
	N	61	38	53	36	14	14	17	8.6	12
Sep	D	0	14	33	47	13	8.0	11	7.8	4.6
	N	49	23	47	40	13	12	13	11	7.5
Oct	D	0	14	61	76	24	14	20	13	10
	N	51	29	87	54	19	19	20	14	13
Nov	D	44	4.4	13	17	5.0	2.9	5.0	3.4	1.9
	N	25	12	18	15	5.7	6.0	6.1	5.2	4.3
Dec	D	2.2	4.1	19	35	10	4.8	7.6	6.2	4.2
	N	31	16	49	67	22	16	17	17	13

* $a=O_{max}$

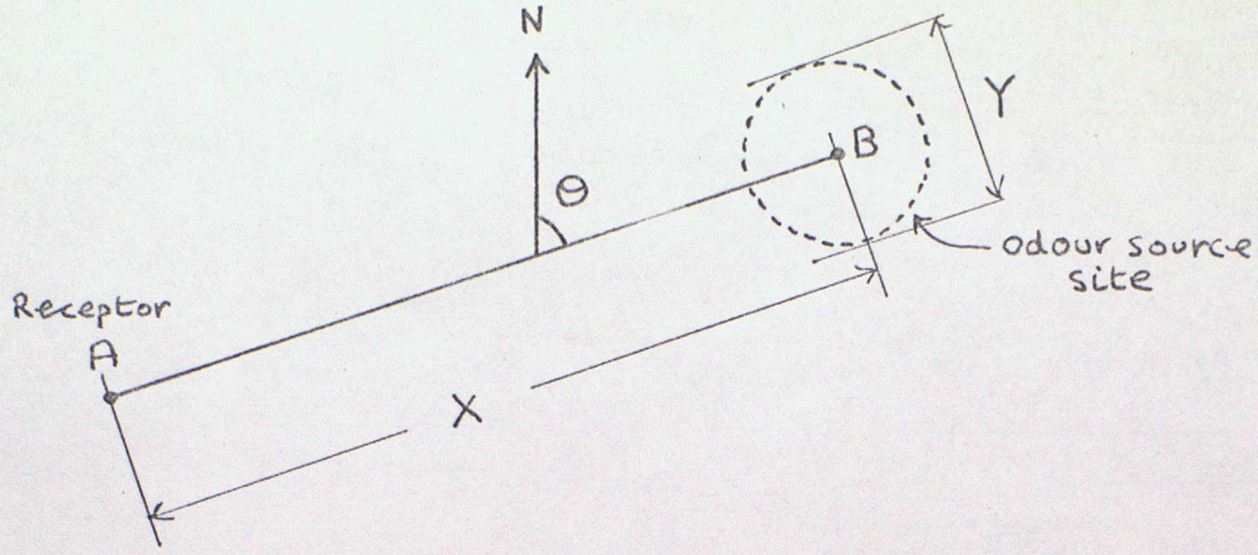

Fig 1. Source/receptor relationship

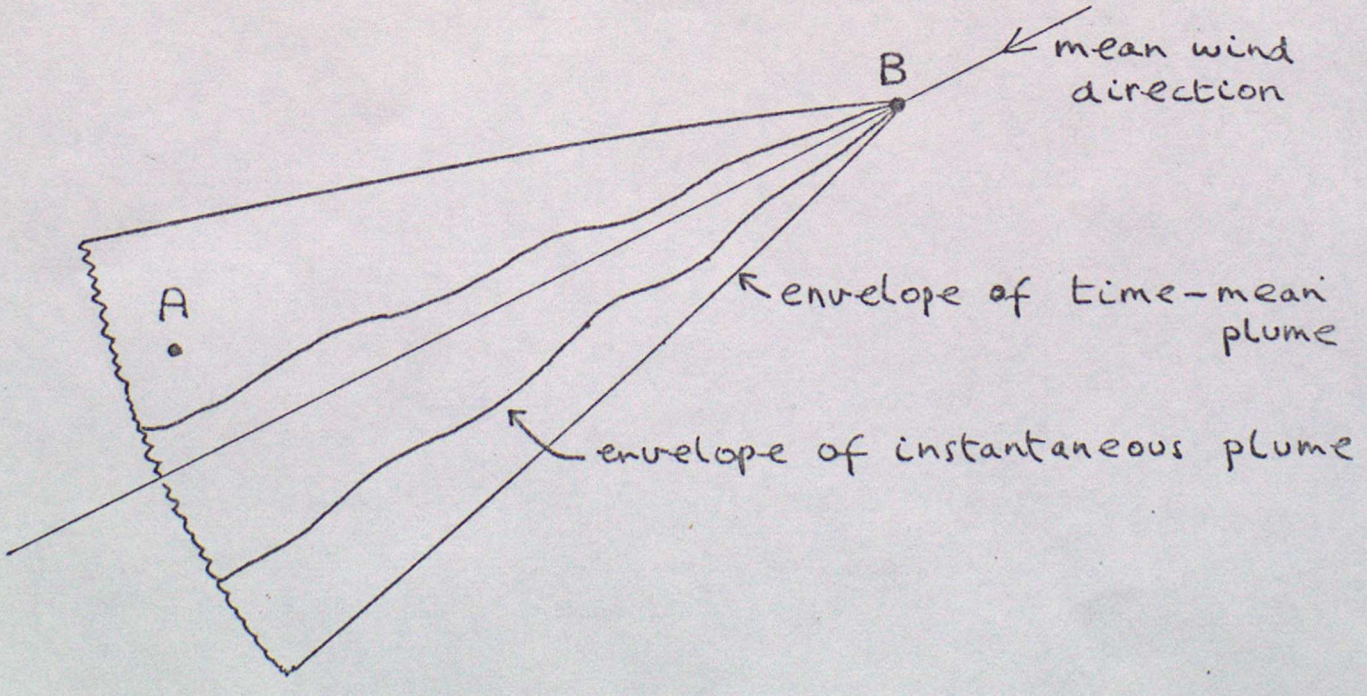

Fig 2. Instantaneous and time-mean odour plumes from a point source

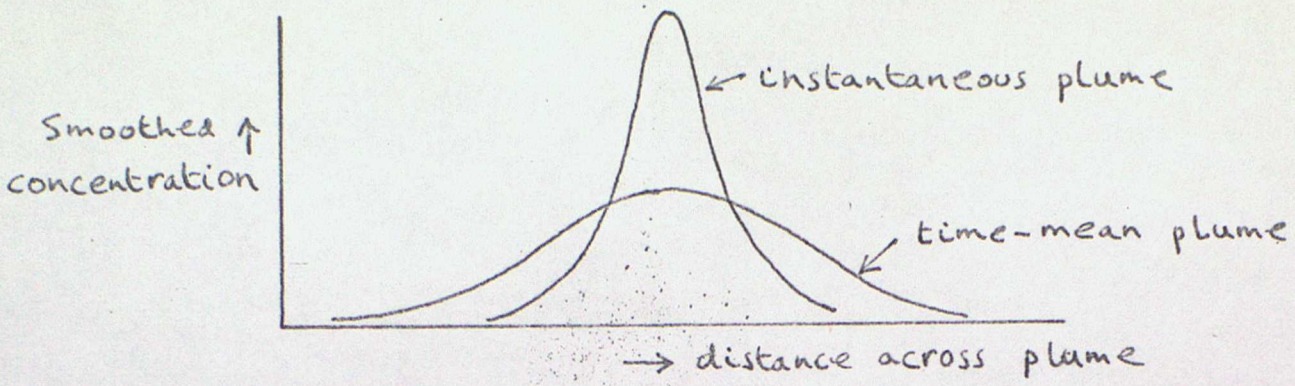

Fig 3. Concentration variations across plumes from point source

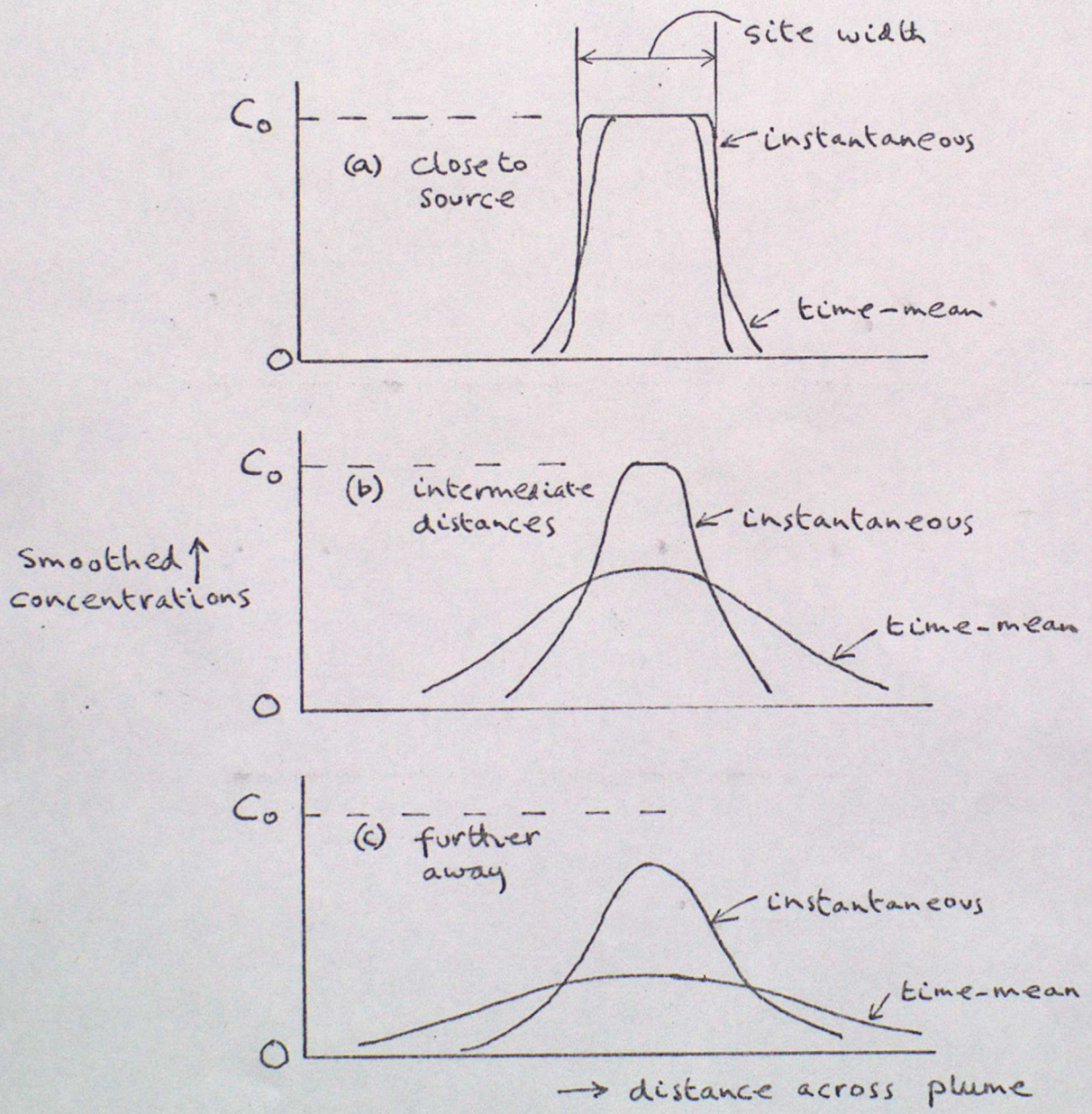

Fig 4. Instantaneous and time-mean concentrations downwind from source area, ignoring dilution due to vertical diffusion

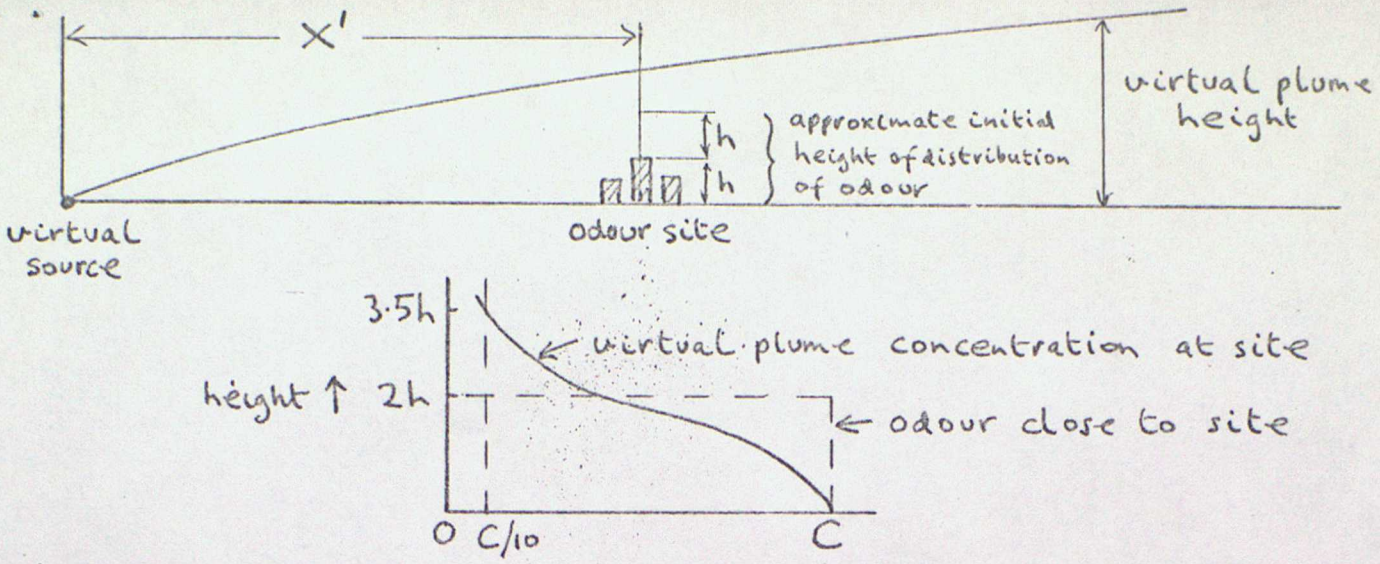

Fig 5. Vertical distribution of concentration from virtual source and odour site

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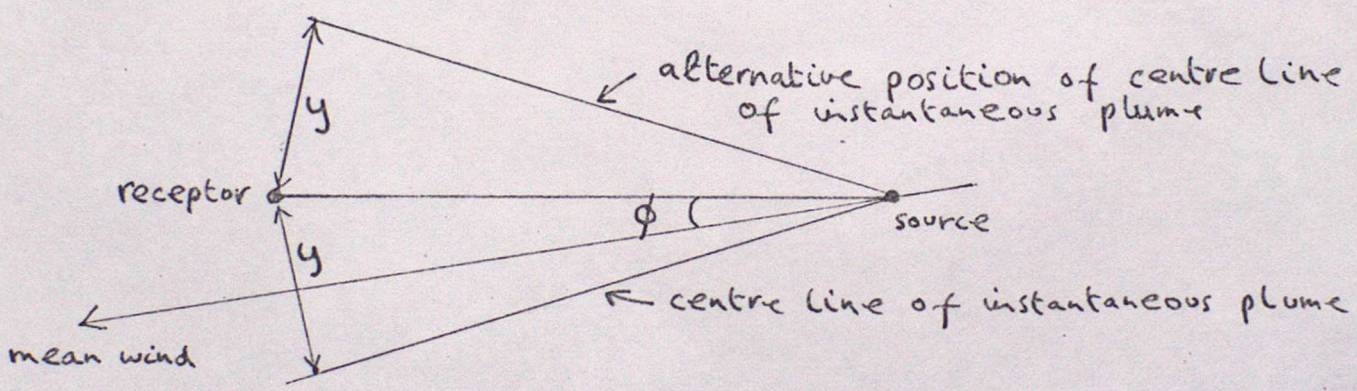

Fig 6. Estimating instantaneous odour concentrations at receptor for a point source

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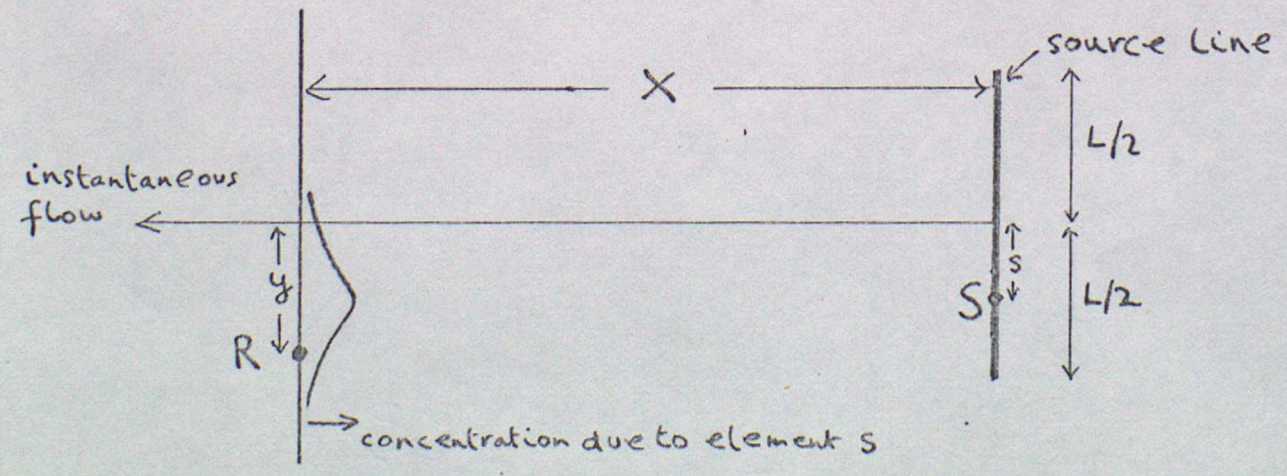

Fig 7. Concentrations downwind from a line source